Final Progress Report for
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Solar Cycle Variation and Multipoint Studies of ICME Properties
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1. Introduction

The goal of the Living With a Star program is to understand the Sun-Earth connection sufficiently well that we can solve problems critical to life and society. This can most effectively be done in the short term using observations from our past and on-going programs. Not only can this approach solve some of the pressing issues but also it can provide ideas for the deployment of future spacecraft in the LWS program. The proposed effort uses data from NEAR, SOHO, Wind, ACE and Pioneer Venus in quadrature, multipoint, and solar cycle studies to study the interplanetary coronal mass ejection and its role in the magnetic flux cycle of the Sun.

ICMEs are most important to the LWS objectives because the solar wind conditions associated with these structures are the most geoeffective of any solar wind phenomena [Lindsay et al., 1995]. Their ability to produce strong geomagnetic disturbances arises first because of their high speed. This high speed overtakes the ambient solar wind producing a bow shock wave similar to the terrestrial bow shock. In the new techniques we develop as part of this effort we exploit this feature of ICMEs. This shocked plasma has a greater velocity, higher density and stronger magnetic field than the ambient solar wind, conditions that can enhance geomagnetic activity. The driving ICME is a large magnetic structure expanding outward in the solar wind [Gosling, 1996]. The ICMEs magnetic field is generally much higher than that in the ambient solar wind and the velocity is high. The twisted nature of the magnetic field in an ICME almost ensures that sometime during the ICME conditions favorable for geomagnetic storm initiation will occur.

To make early rapid progress in the objectives of the Living with a Star program we must exploit existing data sets and on-going space missions. To obtain data over the solar cycle we use the existing magnetic field and plasma data obtained by the Pioneer Venus spacecraft from 1978 to 1988 and the Wind magnetic field and plasma data from 1994 to 2004. To relate the structure of ICMEs to their causative CMEs on the Sun, we use the magnetic field data from the NEAR spacecraft in conjunction with SOHO images at times when NEAR is above the limbs of the Sun as seen from Earth (i.e. quadrature studies). To move away from overly simple models of ICME structure we exploit multipoint measurements of ICMEs using chance conjunctions of interplanetary spacecraft including Pioneer Venus and ISEE3, NEAR and Wind, as well as (on shorter baselines) the Wind-ACE pair. These multipoint studies allow us to prepare for the operation of the dual satellite STEREO mission as well as to give us direction for deploying follow-on multi-spacecraft missions.

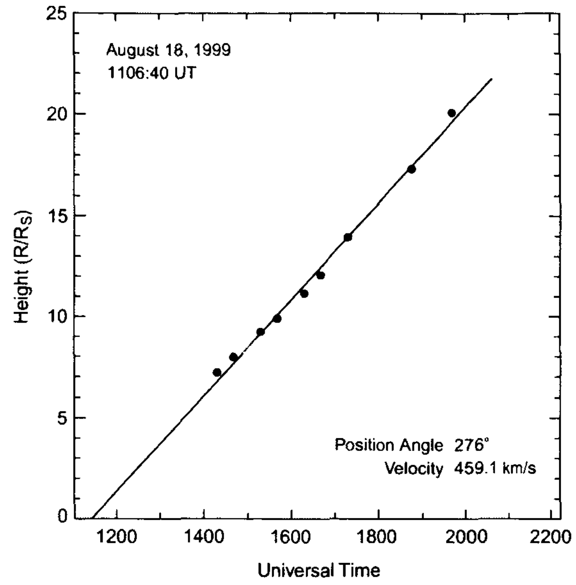

Figure 1. Coronal speeds associated with CME later observed by NEAR above the same limb of the Sun.

Reference

J. T. Gosling, Corotating and transient solar wind flows in three dimensions, in Annual review of astronomy and astrophysics, 34, (revised edition). Edited by: G. Burbridge, A. Sandage, Palo Alto, CA, *Annual Review*, 35-73, 1996.

2. Progress Report

Two quadrature studies were initiated, one with Chris St Cyr and one with Dave Rust. In the former study St Cyr measured the velocity of the CME in the corona and T. Mulligan calculated the transit speed to NEAR. These speeds agreed with no acceleration or deceleration of the ICME. The coronal speeds are shown in Figure 1. In the second study T. Mulligan inverted the properties of ICMEs and provided them to D. Rust for his comparison with solar magnetic structure. As part of this effort a dataset of NEAR magnetic measurements has been prepared and a website (http://www-ssc.igpp.ucla.edu/forms/polar/corr_data_new.html) provides plots and datasets to the community.

Next we have examined the ACE and NEAR data during the Bastille Day event and during the August 13, 2000 event. The former event is excellent for defining the expansion of ICME radii with heliocentric distance [3.1, 3.8, 4.2, 4.5, 4.6 and 5.1]. The second event is well suited for determining the bend in the axial field of a magnetic rope [3.8, 4.2, 4.5, 4.6, 5.1].

Then we examined the PVO observations of ICMEs over a solar cycle. We specifically examined how twisted the ropes were and the force-balance in the ropes. In most ropes the forces had a net outward component unless there was force balance, and there was some correlation of twistedness and this force imbalance. The ropes generally had a twist unlike that in a Bessel function flux rope [5.1]. This observation inspired an examination of the limitations of the Bessel function approach. These disadvantages were discussed at several conferences [4.3, 4.4, 4.7] and a published paper [3.8].

As expected Tamitha Mulligan finished her dissertation, albeit a little later than expected [5.1]. Liz Jensen was able to begin work on the project with a new approach to determining flux rope orientation [4.16, 4.20, 4.22] and an undergraduate student Aniketa Shinde also assisted in identifying events and visualization of rope structure. Shinde's work led to a method to identify ICMEs principally by their solar wind ion signatures [3.10, 4.11, 4.14, 4.15, 4.18]. She also completed a study that classified ICMEs by the strength of their signatures in different parameters and then contrasted her identification with those of other groups. This study has been slowed in the publication process by a referee who does not like what the comparison shows about his list [3.11, 4.23, 4.26]. After A. Shinde graduated this work was advanced by a new graduate student, L. Jian, who combined the plasma and magnetic field data to obtain the total pressure (perpendicular to the field). This parameter smoothly varies with occasional jumps due to shocks. The parameter provides diagnostics of ICMEs that are not obvious from the individual parameters and in addition can be used to characterize and identify stream interactions [4.27, 4.32, 4.33].

Finally, the grant supported the publication of the PVO-ISEE study [3.1] a tutorial on the solar wind and space weather [3.2] a discussion of why we use the term ICME [3.3] and an invited review on ICMEs [4.1] and a contributed review [3.9]. We have also initiated a study of the expansion of ICMEs as evidenced by the velocity variation in the solar wind plasma as the ICME passes [4.11, 4.14] and an ACE-Wind study of small scale structure [4.12]. L. Jensen who is taking over T. Mulligan's efforts is also examining the solar coronal magnetic field via Faraday rotation using the Cassini spacecraft [3.12, 4.13, 4.30, 4.31]. The grant helped support our study of interplanetary field enhancements [4.17] and studies of the Halloween event [4.21, 4.24, 4.28].

3. Papers in Journals and Books (05/1/01 – 02/28/03)

3.1 T. Mulligan, and C. T. Russell, Multispacecraft modeling of the flux rope structure of interplanetary coronal mass ejections: Cylindrically symmetric versus nonsymmetric topologies, *J. Geophys. Res.*, *106*, 10,581-10,596, 2001.

3.2 C. T. Russell, Solar wind and interplanetary magnetic field: A tutorial, in Space Weather, *Geophys. Mono. Series*, *125*, ed. by P. Song, H. J. Singer, and G. L. Siscoe, 73-89, American Geophysical Union, Washington, 2001.

3.3 C. T. Russell, In defense of the term ICME, *EOS*, *Trans. AGU*, *82*(39) 434, 2001.

3.4 T. Mulligan, C. T. Russell, B. J. Anderson, and M. H. Acuna, Multiple spacecraft flux rope modeling of the Bastille Day magnetic cloud, *Geophys. Res. Lett.*, *28*, 4417-4420, 2001.

3.5 C. T. Russell, and T. Mulligan, The true dimensions of interplanetary coronal mass ejections, *Adv. Space Res.*, *29*(3), 301-306, 2002.

3.6 C. T. Russell, and T. Mulligan, On the magnetosheath thicknesses of interplanetary coronal mass ejections, *Planet. Space Sci.*, *50*(5/6), 527-534, 2002.

3.7 C. T. Russell, T. Mulligan, and B. J. Anderson, Radial variation of magnetic flux ropes: Case studies with ACE and NEAR, in *Solar Wind Ten: Proceedings of the Tenth International Solar Wind Conference*, edited by M. Velli, R. Bruno, and F. Malara, American Institute of Physics, 121-124, 2003.

3.8 C. T. Russell, and T. Mulligan, The limitation of Bessel functions for ICME modeling, in *Solar Wind Ten: Proceedings of the Tenth International Solar Wind Conference*, edited by M. Velli, R. Bruno, and F. Malara, American Institute of Physics, 125-128, 2003.

3.9 M. B. Moldwin, P. C. Liewer, N. Crooker, J. F. Fennell, J. Feynman, H. O. Funsten, B. E. Goldstein, J. T. Gosling, J. E. Mazur, V. J. Pizzo, C. T. Russell, and J. Weygand, Heliospheric Constellation: Understanding the structure and evolution of the solar wind, in *Solar Wind Ten: Proceedings of the Tenth International Solar Wind Conference*, edited by M. Velli, R. Bruno, and F. Malara, American Institute of Physics, 842-845, 2003.

3.10 C. T. Russell, and A. A. Shinde, ICME identification from solar wind ion measurements, *Solar Physics*, 216, 285-294, 2003.

3.11 C. T. Russell and A. A. Shinde, On defining interplanetary coronal mass ejection from fluid parameters, Solar Physics, submitted, 2004.

3.12 E. A. Jensen, M. K. Bird, S. W. Asmar, L. Iess, and C. T. Russell, The Cassini Solar Faraday rotation experiment, *Adv. Space Res.*, submitted, 2005.

3.13 C. T. Russell, A. A. Shinde, and L. Jian, A new parameter to define interplanetary coronal mass ejections, *Adv. Space Res.*, submitted, 2005.

4. Papers Presented at Meetings (05/1/01 – 02/28/03)

4.1 T. Mulligan, Interplanetary coronal mass ejections and their solar origins, presented at the SHINE Joint Workshop with GEM, (organizers: D. Webb and M. K. Hudson), Snowmass, Colorado, June, 2001.

4.2 C. T. Russell, T. Mulligan and B. J. Anderson, Radial expansion at magnetic clouds, presented at the First STEREO Workshop, Paris, March 2002.

4.3 C. T. Russell and T. Mulligan, Advantages of a non-force-free approach to modeling magnetic clouds, presented at the First STEREO Workshop, Paris, France, March, 2002.

4.4 C. T. Russell and T. Mulligan, On the limitations of Taylor-State force-free models of interplanetary coronal mass ejection, presented at EGS General Assembly, Nice, France, April 2002.

4.5 C. T. Russell, T. Mulligan and B. J. Anderson, Variation of magnetic flux ropes with heliocentric distance, presented at EGS General Assembly, Nice, France, April 2002.

4.6 C. T. Russell, T. Mulligan and B. J. Anderson, Radial variation of magnetic flux ropes: Case studies with ACE and NEAR, presented at Solar Wind 10, Pisa, Italy, June 2002.

4.7 C. T. Russell and T. Mulligan, The limitation of Bessel Functions for ICME modeling, presented at Solar Wind 10, Pisa, Italy, June 2002.

4.8 E. A. Jensen, M. K. Bird, M. Patzold, C. T. Russell, J. P. Anderson and S. W. Asmor, Initial results of 2 R_o south polar magnetic field from 2002 Cassini conjuntion, presented at SHINE 2002, Banff, Alberta, August 2002.

4.9 C. T. Russell, T. Mulligan and B. J. Anderson, Heliospheric radial variation of ICMEs, presented at SHINE 2002, Banff, Alberta, August 2002.

4.10 C. T. Russell and T. Mulligan, A comparison of approaches to modeling ICMEs, presented at SHINE 2002, Banff, Alberta, August 2002.

4.11 A. A. Shinde and C. T. Russell, ICME Identification from solar wind ion measurements, presented at SHINE 2002, Banff, Alberta, August 2002.

4.12 G. H. Jones, C. T. Russell, A. A. Shinde and A. Balogh, Interplanetary field enhancements - evidence of an interaction between the solar and interplanetary dust, presented at the Fall American Geophysical Union meeting, (abstract) in *Supplement to Eos. Trans. AGU*, *83*(47), p.F815, 2002.

4.13 E. A. Jensen, M. K. Bird, M. Paetzold, S. W. Asmar, J. D. Anderson, L. Iess and C. T. Russell, Initial results from the Cassini solar conjunction Faraday rotation experiment, presented at the Fall American Geophysical Union meeting, (abstract) in *Supplement to Eos. Trans. AGU*, *83*(47), p.F1133, 2002.

4.14 A. A. Shinde and C. T. Russell, ICME identification from solar wind ion measurements, presented at the Fall American Geophysical Union meeting, (abstract) in *Supplement to Eos. Trans. AGU*, *83*(47), p.F1159, 2002.

4.15 C. T. Russell and A. A. Shinde, ICME Expansion, presented at EGS-AGU-EUG Joint Assembly, Nice, France, April 2003.

4.16 E. A. Jensen, T. Mulligan, and C. T. Russell, Using vector analysis to reveal ICME orientation, presented at SHINE Meeting, Maui, July 2003.

4.17 C. T. Russell, and A. A. Shinde, Interplanetary Field enhancements, presented at the SHINE Meeting, Maui, July 2003.

4.18 A. A. Shinde, and C. T. Russell, A Study of ICME expansion, presented at the SHINE Meting, Maui, July 2003.

4.19 A. A. Shinde, and C. T. Russell, What defines an interplanetary coronal mass ejection? Eos. Trans. AGU, 84(46), p.F1201, Fall Meeting Suppl., Abstract SH21B-0133, 2003.

4.20 E. A. Jensen, C. T. Russell, and T. Mulligan, A simple method for determining the time of closest approach to the center of a magnetic fluxrope, Eos. Trans. AGU, 84(46), p.F1223, Fall Meeting Suppl., Abstract SH41B-0467, 2003.

4.21 C. T. Russell, G. Delory, M. Dougherty, D. Lario, J. G. Luhmann, R. Skoug and C. W. Smith, Heliospheric response to the solar events of October and November, 2003, presented at the EGU First General Assembly, Nice, France, April 2004.

4.22 E. A. Jensen, C. T. Russell, Determining the time of closest approach to the center of magnetic flux ropes, presented at the EGU First General Assembly, Nice, France, April 2004.

4.23 C. T. Russell, and A. A. Shinde, Intercomparisons of ICME identifications, presented at the EGU First General Assembly, Nice, France, April 2004.

4.24 D. Lario, S. Livi, S. M. Krimigis, R. B. McKibben, C. G. Maclennan, D. B. Reisenfeld, C. de Koning, C. T. Russell, and M. K. Dougherty, Heliospheric energetic particle observations during the October-November 2003 superstorm events, presented at Spring AGU Meeting (abstract) Eos. Trans. AGU, 85(17), Joint Assembly Suppl., Abstract SH33A-03, p.JA384, May 2004.

4.25 C. T. Russell, R. Skoug, C. W. Smith, G. Delory, and M. Dougherty, The October/November 2003 storms: Heliospheric disturbances, 13th Annual GEM Meeting, Snowmass, CO, June 2004.

4.26 A. A. Shinde, C. T. Russell, and L. Jian, What defines an interplanetary coronal mass ejection? SHINE Meeting, Big Sky, Montana, June 2004.

4.27 C. T. Russell, A. A. Shinde, and L. Jian, A new parameter for characterizing ICMEs, SHINE Meeting, Big Sky, Montana, June 2004.

4.28 C. T. Russell, J. Luhmann, C. W. Smith, R. Skoug, M. Dougherty, D. Lario, and L. Jian, The October/November 2003 solar events: Heliospheric disturbances, SHINE Meeting, Big Sky, Montana, June 2004.

4.29 C. T. Russell, and A. A. Shinde, What defines an interplanetary coronal mass ejection, presented at the 35th COSPAR Scientific Assembly, Paris, France, July 2004.

4.30 E. A. Jensen, M. K. Bird, S. W. Asmar, J. D. Anderson, and C. T. Russell, The Cassini Solar Faraday rotation experiment, presented at the 35th COSPAR Scientific Assembly, Paris, France, July 2004.

4.31 E. A. Jensen, M. K. Bird, S. Asmar, L. Iess, J. G. Luhmann, J. D. Anderson, and C. T. Russell, Solar Coronal Transients Observed during the Cassini Faraday Rotation experiment, presented at Sun-Earth Connection Physics: The GeoImpact of CMEs, CIRs, and Ordinary Solar Wind, Merida, Mexico, November 2004.

4.32 L. Jian, C. T. Russell, and J. T. Gosling, Using the total perpendicular pressure to diagnose corotating interaction regions and ICMEs, presented at Sun-Earth Connection Physics: The GeoImpact of CMEs, CIRs, and Ordinary Solar Wind, Merida, Mexico, November 2004.

4.33 L. Jian, C. T. Russell, and J. T. Gosling, Diagnostics of solar wind processes using the total perpendicular pressure, presented at Fall AGU Meeting, Eos. Trans. AGU, 85(47), Fall Meeting Supl., Abstract SH23A-04, F1491, 2004.

5. Thesis

T. Mulligan, The structure of interplanetary coronal mass ejections and their solar origins, Ph.D Dissertation March, 2002.